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RESEARCH ARTICLE
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Water Rights Allocation Versus Actual Crop Water Requirements: A Case Study of South Amman Wastewater Treatment Plant, Jordan

Ali Brezat [1,*], Ahmad Abu-Awwad [1] and Rasha Al-Rkebat [2]

[1]Department of Land, Water and Environment, School of Agriculture, University of Jordan, The University of Jordan 11942, Jordan
[2]Department of Environmental Systems Research, National Agricultural Research Center, Baq'a 19381, Jordan
*Corresponding author: ali.omar.brezat@gmail.com

ABSTRACT

Jordan is in the middle of a severe water crisis; hence, the national water security policy relies heavily on non-traditional water sources, such as treated wastewater (TWW), notably for farming. The FAO Penman-Monteith equations, FAO crop coefficient, and CROPWAT software were used to analyze meteorological data (1980–2010) and estimate the water requirements of four major crops: olives (95.5ha), alfalfa (289ha), barley (280ha), and vetch (297.6ha). The results showed that the annual TWW supply (12,766,064m^3 year^{-1}) was quite different from the estimated actual agricultural need (7,173,601m^3 year^{-1}). This meant that there was a annual surplus of 43.8% (5,592,463m^3 year^{-1}). The present fixed allocation scheme (30m^{3}ha^{-1} day^{-1}) was very inefficient since it gave too much to barley and vetch and not enough to alfalfa. Even though alfalfa only took up 30% of the land, it used 56.4% of the total water. Olives, on the other hand, were the most efficient at using water (9400m^3 ha^{-1} year^{-1}). The results show that we need to move from fixed to dynamic allocation systems that respond to crops' real needs immediately. We also need to use seasonal storage solutions to make use of the extra water. This will support Jordan's water security strategy and ensure the best, most sustainable use of TWW.

Keywords: Treated wastewater reuse; Agricultural water management; Water use efficiency; Water rights; Crop water requirements; Dynamic allocation; Jordan; Arid regions.

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INTRODUCTION

The shortage of water is becoming a growing problem in dry and semi-arid regions across the globe. This crisis is increasingly exacerbated by the effects of climate change, rapid population expansion, and rising water demand from industrial, municipal, and agricultural sectors (Mahmoud, 2025). In this context, the reuse of non-traditional water resources, particularly treated wastewater (TWW), has emerged as a cornerstone strategy to promote water sustainability and resource efficiency. Globally, water reuse is now recognized as an integral component of sustainable water management under the United Nations Sustainable Development Goals (SDG 6 and SDG 13), emphasizing clean water access and climate adaptation. In arid and semi-arid regions such as the Middle East and North Africa (MENA), where over 60% of the population faces severe water stress, wastewater reuse has become a policy imperative to close the water–food gap (Maher et al., 2025). Countries like Egypt, Saudi Arabia, and Jordan have prioritized wastewater reuse programs to offset freshwater scarcity and enhance agricultural resilience. The Food and Agriculture Organization (FAO) and World Bank have also advocated water reuse as an essential adaptation measure for achieving food security in water-scarce economies (FAO, 2020).

The reuse of TWW is gaining increasing attention worldwide as an integral component of comprehensive water resource management strategies in arid regions (Dawoud et al., 2012). Beyond augmenting water supply, TWW offers agronomic benefits by providing nutrients such as nitrogen, phosphorus, and potassium, which can substantially reduce the need for costly chemical fertilizers (Obijianya et al., 2025). From both environmental and economic standpoints, integrating wastewater reuse into agricultural systems represents a practical and sustainable approach to mitigating the dual challenge of water scarcity and nutrient depletion in soils (Sei et al., 2025).

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Jordan exemplifies these challenges vividly. It is one of the most water-scarce countries in the world, facing severe pressure on its limited water resources due to urban population growth and increased potable water demand. The country's expanding cities consume large quantities of freshwater, intensifying the national water deficit. Per capita water availability in Jordan is currently around 90m^3 year^{-1} (Al-Addous et al., 2023), placing it among the ten most water-poor nations globally. This Fig is projected to fall to only 60m^3 year^{-1} by 2040 due to population growth, low rainfall, and climate change (Dawoud et al., 2012). Over-extraction has further aggravated the crisis: groundwater is being exploited at about 130% of its safe yield, leading to declining water tables and increased salinity (Obijianya et al., 2025). The chronic water shortage not only constrains domestic supply but also hampers economic development and agricultural productivity. Despite consuming nearly half of Jordan's total water resources, the agricultural sector contributes only around 5% to the country's Gross Domestic Product (GDP) (FAO, 2020).

In response to these escalating pressures, Jordan has adopted ambitious national water policies focused on maximizing the productive reuse of TWW. More than 90% of the country's wastewater is now collected and treated, with the majority reused for agricultural purposes (Alvarez-Holguin et al., 2022). This aligns with the National Water Strategy (2023–2040), which explicitly prioritizes the use of TWW in agriculture to relieve pressure on limited freshwater reserves (Sdiri et al., 2023). The strategy promotes optimizing non-conventional water use through integrated water resources management (IWRM), efficiency improvements, and alignment with national food security objectives. Similar approaches are being implemented across the Gulf and North African countries—such as Abu Dhabi, where TWW contributes about 7.2% of the total water supply—underscoring its regional strategic importance (Dawoud et al., 2012).

From an agronomic and physiological perspective, efficient irrigation management must account for the dynamic water requirements of crops throughout their growth stages. The crop coefficient (KC) represents the ratio of actual crop evapotranspiration to reference evapotranspiration, and it varies significantly across phenological stages. Early growth phases typically require lower water input, while mid-season stages with full canopy cover exhibit peak evapotranspiration and higher water demand. Ignoring these variations results in either under- or over-irrigation, adversely affecting crop yield, water-use efficiency, and soil salinity balance. Therefore, irrigation scheduling based on Kc dynamics is essential for aligning water allocations with actual crop needs and ensuring the sustainable utilization of limited TWW resources (Aziz et al., 2025).

Despite these well-established agronomic principles, many irrigation systems, especially those relying on TWW, still depend on fixed allocation schemes that do not reflect temporal or spatial variations in crop water demand. Such practices are prevalent in Jordan's agricultural sector, where water allocation is often determined on a per-hectare or per-day basis, irrespective of crop type or growth stage. This approach is not only inefficient but can also lead to waterlogging, salinity build-up, or yield reduction, depending on the mismatch between supply and demand (Shuai & Basso, 2022). From a management and economic standpoint, dynamic allocation systems, which adjust supply based on real-time evapotranspiration, climatic conditions, and crop growth—offer superior efficiency. These systems can optimize water productivity, minimize operational costs, and enhance farmers' net returns by reducing wastage and ensuring equitable distribution among users. Conversely, fixed quota systems can cause resource misallocation and high opportunity costs for both utilities and end-users (Ahmed et al., 2023).

The South Amman Wastewater Treatment Plant (SAWWTP), operational since 2015, embodies these challenges. The plant produces large volumes of TWW suitable for agricultural reuse; however, the current allocation mechanism is static, providing a fixed share of 30m^3 per hectare per day. This system disregards the substantial differences in water requirements among major crops such as olives, alfalfa, barley, and vetch, as well as seasonal fluctuations in demand (Abu-Awwad, 2021). Consequently, the fixed allocation model results in inefficiencies and diverges from the principles of demand-driven irrigation management. Studies have shown that such traditional, static water allocation frameworks often fail to match the actual crop water requirement, leading to discrepancies between planned and actual usage (Hou et al., 2023).

Addressing this issue requires bridging the gap between national policy frameworks and on-the-ground operational practices. While Jordan's national strategy emphasizes wastewater reuse and efficiency optimization, practical implementation still relies heavily on outdated allocation systems. This study aims to assess the discrepancy between allocated water rights and actual crop water requirements using data from the SAWWTP service area. By evaluating the magnitude of deviation between fixed and actual water demand, the research contributes to the implementation goals of the National Water Strategy (2023–2040) specifically, its call for enhancing allocation efficiency and integrating scientific irrigation management tools to support sustainable agriculture (MWI, 2023).

There remains a considerable gap between the strategic ambitions outlined at the policy level and the operational realities faced by end-users. Although previous studies in Jordan have examined TWW quality, infrastructure, and general reuse practices (Abu-Awwad, 2021), few have investigated the efficiency of allocation mechanisms relative to actual crop demand. The present study addresses this gap by quantifying the misalignment between fixed allocations and crop-specific water requirements, thereby identifying potential efficiency gains. This is crucial because ineffective allocation systems waste a highly treated and costly resource, undermining both environmental and economic sustainability (Mancuso et al., 2022).

This study aims to fill the gap mentioned by providing a comprehensive analysis module of the efficiency of TWW use in the SAWWTP area and will be valid for the WWTPs. The study endeavors to: (1) assess and analyze the monthly and annual supply patterns of TWW from SAWWTP, (2) estimate the water requirements of the main crops grown in the area, (3) assess the balance between supply and demand, (4) develop crop actual water use efficiency indicators, and (5) compare current water allocations with actual requirements. In doing so, this study not only offers a technical assessment of a local water system but also provides evidence-based insights that can contribute to improving policies and developing water management practices in line with Jordan's strategic water security goals.

MATERIALS & METHODS

Study Area Description and Data Collection

The SAWWTP is in the Southern part of Greater Amman at an elevation of 690m above sea level. It was operated in 2015 to serve the densely populated southern part of Amman. It is the 2nd largest WWTP in Jordan. The existing SAWWTP provides treatment through extended aeration process. This should be converted to Conventional Activated Sludge Process. The work covered under the investment contract involves both the refurbishment of existing facilities as well as the construction of new facilities to upgrade the level of treatment with sludge digestion and biogas generation. Fig. 1 shows the map of the study area.

Climatic and precipitation data were collected from the Ministry of Water and Irrigation's stations: Queen Alia International Airport (QAIA) and Al-Mushaqqar, for the period from 1980 to 2010. Daily records included maximum and minimum air temperatures (°C), dry- and wet-bulb humidity readings (°C), maximum wind velocity (km h^{-1}), and total daily precipitation (mm). Supplementary agricultural statistics, specifically the area of irrigated land and the spatial distribution of predominant crops; olives, alfalfa, barley, and vetch were also compiled to support subsequent water budget assessments.

The effluent characteristics of SAWWTP results were evaluated against the Jordanian Standards (JS 1776/2013) (Al Arni et al., 2022) to determine the suitability of the treated water for reuse in irrigation and other applications. Table 1 represents the effluent quality standards for irrigating different crops with the allowable limits, showing that stricter thresholds, especially for Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Total Nitrogen (TN), Phosphate (PO_4) and potential hydrogen (pH), are required to ensure safe reuse in agriculture.

Table 1: The standard quality of treated wastewater and effluent characteristics of the SAWWTP

Parameter	Effluent Quality Jordanian Standards (JS 1776/2013)	SAWWTP Effluent Quality
BOD (mg/L)	200	54.5
COD (mg/L)	300	104.3
TSS (mg/L)	100	44
TN (mg/L)	70	21
PO_4 (mg/L)	10	7.1
pH (lower limit)	6	7.2

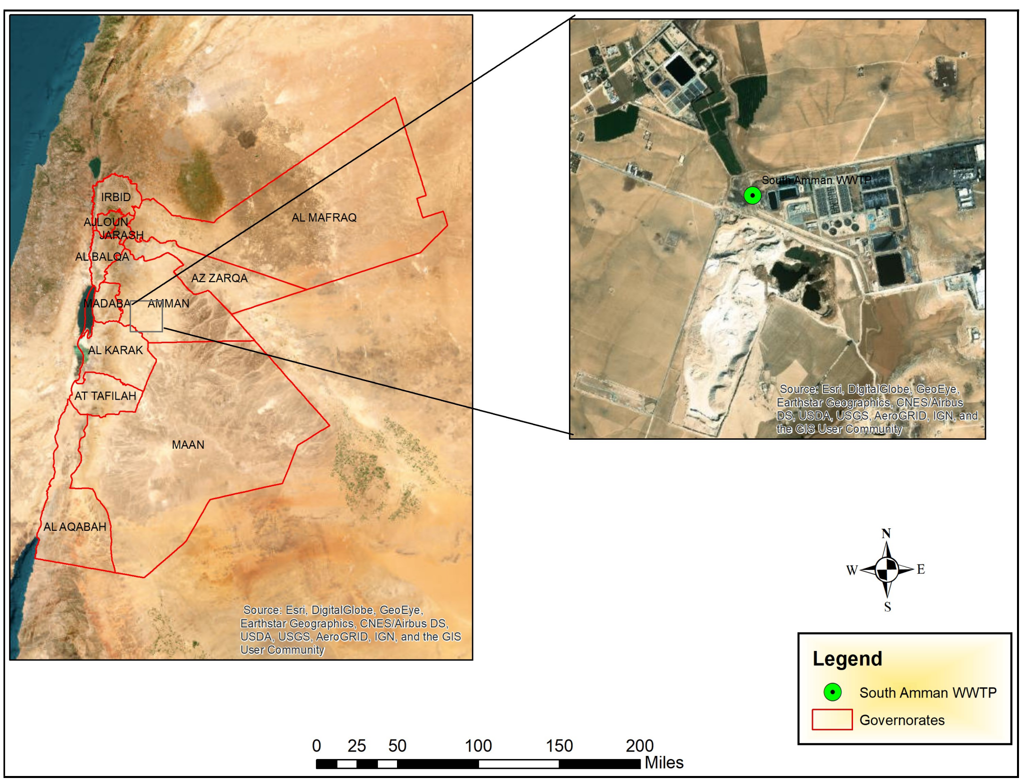

Fig. 1: Location of the study area.

Computational Framework

In this study, the methodology draws inspiration from Abu-Awwad (2011), who developed and tested a model to optimize cropping patterns for maximizing the reuse of TWW effluent from Wadi Musa WWTP. The cultivated crops in that study included alfalfa, winter grains, fodder, olives, and fruit trees. The model utilized effluent supply data and peak period crop water requirements to calculate the optimal crop area for various combinations of recommended crops. For this research, a similar optimization approach will be applied, focusing on the SAWWTP. The study will target different crops, specifically forage crops suitable for the South Amman region. By considering effluent supply and the water requirements of selected crops, the model will calculate the best cropping pattern to maximize the use of TWW. The goal is to optimize and/or maximize the effluent usage across the year, minimize surplus and reliance on storage facilities, and enhance sustainable agricultural practices in South Amman.

Effective Precipitation (*Pe*)

Historical rainfall series from both stations were aggregated into monthly sums before being input into the FAO's CROPWAT 8.0 software (FAO, 2025a; Fig. A1). Using the FAO recommended methodology, rainfall probabilities at the 70% level were extracted to obtain dependable precipitation estimates (FAO, 2025a). Outputs were expressed in mm day^{-1}, with soil texture and water-holding characteristics incorporated into the final effective precipitation (*Pe*) values for crop. The QAIA and Al-Mushaqqar stations weighting was 80% and 20%, respectively.

Crop Coefficient (*KC*)

Crop coefficients were assigned in accordance with FAO-56 guidelines (Allen et al., 1998). For each crop (olive, alfalfa, barley, and vetch) key phenological phases (initial, development, mid-season, late-season) were identified. A time-weighted average crop coefficient ($\overline{KC}$) was computed via Equation (1):

$$\overline{KC} = \frac{\sum_{i=1}^{n} KC_i \times duration_i}{\sum_{i=1}^{n} duration_i} \qquad (1)$$

Where, KC_i is the crop coefficient for stage *i*, and $duration_i$ is the duration of stage *i* in days. Seasonal ranges for the *KC* for each crop are represented in Table 2, reflecting variation across cutting cycles and growth intervals.

Reference Evapotranspiration *(ET$_O$)*

Daily reference evapotranspiration *(ET$_O$)* rates were derived through the Penman-Monteith equation, implemented in the FAO ET calculator Version 8.0 (FAO, 2025b). Input parameters were set as in Section 2.1. Climatic variables were processed by FAO-56 guidelines to generate values in (mm day^{-1}), which were then averaged monthly.

Crop Evapotranspiration (*ET$_C$*) and Net Irrigation Requirement (*NIR*)

Crop evapotranspiration (ET_C) was calculated as the product of the *KC* and ET_O for each day, then aggregated into monthly averages. The Net Irrigation Requirement (*NIR*) was obtained by subtracting *Pe* from ET_c as shown in Equation (2):

$$NIR = ET_C - Pe \qquad (2)$$

Irrigation Efficiency and Gross Water Need

An efficiency coefficient of 0.80, reflecting the performance of sprinklers irrigation systems in the study area, was applied to upscale the net requirement, yielding gross crop water requirements as shown in Equation (3):

$$ET_{C-gross} = \frac{NIR}{0.8} \qquad (3)$$

Monthly Water Demand Calculation

Monthly irrigation volumes (m^3) were determined by multiplying the gross crop evapotranspiration ($ET_{C\text{-}gross}$) (mm day^{-1}) by the irrigated area (dunum) and the number of days in each month, with necessary unit conversions applied (1mm = 10m^3 ha^{-1}). Detailed calculations for the monthly demands for all crops are presented in the Appendix (Table A1-4).

Water Supply Calculation

A uniform water allocation of 30 m^3 ha^{-1} day^{-1} for TWW was used. Daily flow rates at the local wastewater treatment plant were monitored and aggregated into monthly totals.

Statistical Analysis

All quantitative computations and comparative analyses were carried out using Microsoft Excel 2021 and IBM SPSS Statistics v26. Descriptive statistics were applied to summarize climatic variables (temperature, wind speed, humidity, and precipitation) and effluent characteristics of the South Amman Wastewater Treatment Plant (SAWWTP). For each parameter, mean ± standard deviation (SD) and coefficient of variation (CV%) were calculated to evaluate temporal variability.

Table 2: Crop coefficients values for each phenological stage per crop (initial, development, mid, late) and their durations

Crop	Olive		Alfalfa		Barley		Vetch	
Phenological stage	KC	Duration (days)	KC	Duration (days)	KC	Duration (days)	KC	Duration (days)
Initial Stage	0.3	70	0.25	60	0.25	45	0.5	25
Development Stage (Average)	0.7	95	0.85	90	0.7	65	0.75	50
Mid Stage	0.75	110	1.1	125	1	90	1	65
Late Stage (end point)	0.65	90	0.7	90	0.33	70	0.75	40

Sample:

$$\overline{KC}_{Olive\ in\ January} = \frac{\sum_{i=1}^{n} KC_i \times duration_i}{\sum_{i=1}^{n} duration_i} = \frac{0.3 \times 31}{31} = 0.3$$

Table A1: Monthly water demands calculations for Olive cultivation including effective precipitation and crop evapotranspiration

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days of Month	31	28	31	30	31	30	31	31	30	31	30	31
PE (mm day^{-1})	1.2	1.3	0.7	0.2	0.1	0.0	0.0	0.0	0.0	0.1	0.5	0.9
$\overline{KC}$	0.3	0.3	0.3	0.5	0.6	0.7	0.8	0.8	0.8	0.7	0.7	0.7
ET_O (mm day^{-1})	1.9	2.3	3.3	4.3	5.1	5.5	5.7	5.4	4.7	3.5	2.4	1.8
ET_C (mm day^{-1})	0.6	0.7	1.1	2.0	3.1	4.0	4.3	4.0	3.5	2.6	1.7	1.2
$ET_{C\text{-net}}$ (mm day^{-1})	0.0	0.0	0.4	1.8	3.0	4.0	4.3	4.0	3.5	2.5	1.1	0.0
Irrigation Efficiency	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
$ET_{C\text{-gross}}$ (mm day^{-1})	0.0	0.0	0.4	2.2	3.8	5.0	5.3	5.0	4.4	3.1	1.4	0.0
$ET_{C\text{-gross}}$ (mm)	0.0	0.0	13.8	66.6	116.8	151.0	165.1	156.4	132.0	95.8	42.3	0.0
Area (ha)	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5
CWR (m^3)	0	0	13,166	63,588	111,582	144,244	157,702	149,348	126,039	91,502	40,357	0
Supply (m^3)	92,535	83,580	92,535	89,550	92,535	89,550	92,535	92,535	89,550	92,535	89,550	92,535
Effluent (m^3)	1,075,178	885,118	961,683	1,094,040	1,134,166	1,075,486	1,119,844	1,123,874	1,088,200	1,090,073	984,269	1,134,133
Surplus/Deficit (m^3)	92,535	83,580	79,369	25,962	-19,047	-54,694	-65,167	-56,813	-36,489	1,033	49,193	92,535

Table A2: Monthly water demands calculations for Alfalfa cultivation including effective precipitation and crop evapotranspiration

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days of Month	4	28	31	30	31	30	31	31	30	31	30	31
PE (mm day^{-1})	1.2	1.3	0.7	0.2	0.1	0.0	0.0	0.0	0.0	0.1	0.5	0.9
$\overline{KC}$	0.3	0.3	0.4	0.7	1.0	1.1	1.1	1.1	1.1	1.0	0.9	0.8
ET_O (mm day^{-1})	1.9	2.3	3.3	4.3	5.1	5.5	5.7	5.4	4.7	3.5	2.4	1.8
ET_C (mm day^{-1})	0.5	0.6	1.3	2.9	4.9	6.0	6.3	5.9	5.2	3.7	2.1	1.4
$ET_{C\text{-net}}$ (mm day^{-1})	0.0	0.0	0.5	2.8	4.8	6.0	6.3	5.9	5.2	3.6	1.6	0.0
Irrigation Efficiency	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
$ET_{C\text{-gross}}$ (mm day^{-1})	0.0	0.0	0.7	3.4	6.0	7.5	7.8	7.4	6.5	4.4	2.0	0.0
$ET_{C\text{-gross}}$ (mm)	0.0	0.0	21.0	103.0	186.2	226.3	242.2	229.4	193.6	137.6	60.2	0.0
Area (ha)	289	289	289	289	289	289	289	289	289	289	289	289
CWR (m^3)	0	0	60,560	297,680	538,006	653,877	699,944	662,865	559,580	397,730	173,892	0
Supply (m^3)	268,770	242,760	268,770	260,100	268,770	260,100	268,770	268,770	260,100	268,770	260,100	268,770
Effluent (m^3)	1,075,178	885,118	961,683	1,094,040	1,134,166	1,075,486	1,119,844	1,123,874	1,088,200	1,090,073	984,269	1,134,133
Surplus/Deficit (m^3)	268,770	242,760	208,210	-37,580	-269,236	-393,777	-431,174	-394,095	-299,480	-128,960	86,208	268,770

Table A3: Monthly water demands calculations for Barley cultivation including effective precipitation and crop evapotranspiration

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days of Month	31	28	31	30	31	30	31	31	30	31	30	31
PE (mm day^{-1})	1.2	1.3	0.7	0.2	0.1	0.0	0.0	0.0	0.0	0.1	0.5	0.9
$\overline{KC}$	1.0	1.0	1.0	0.9	0.6	0.4	0.0	0.0	0.3	0.3	0.5	0.8
ET_O (mm day^{-1})	1.9	2.3	3.3	4.3	5.1	5.4	5.7	5.4	4.9	3.5	2.4	1.8
ET_C (mm day^{-1})	1.9	2.3	3.3	3.7	3.0	2.1	0.0	0.0	1.2	0.9	1.1	1.5
$ET_{C\text{-net}}$ (mm day^{-1})	0.0	0.0	2.6	3.5	2.9	2.1	0.0	0.0	1.2	0.8	0.5	0.0
Irrigation Efficiency	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
$ET_{C\text{-gross}}$ (mm day^{-1})	0.0	0.0	3.2	4.4	3.6	2.6	0.0	0.0	1.5	1.0	0.7	0.0
$ET_{C\text{-gross}}$ (mm)	0.0	0.0	98.7	131.2	111.6	77.4	0.0	0.0	45.8	29.4	19.8	0.0
Area (ha)	280.4	280.4	280.4	280.4	280.4	280.4	280.4	280.4	280.4	280.4	280.4	280.4
CWR (m^3)	0	0	276,657	367,998	312,945	216,918	0	0	128,406	82,426	55,521	0
Supply (m^3)	260,772	235,536	260,772	252,360	260,772	252,360	260,772	260,772	252,360	260,772	252,360	260,772
Effluent (m^3)	1,075,178	885,118	961,683	1,094,040	1,134,166	1,075,486	1,119,844	1,123,874	1,088,200	1,090,073	984,269	1,134,133
Surplus/Deficit (m^3)	260,772	235,536	-15,885	-115,638	-52,173	35,442	260,772	260,772	123,954	178,346	196,839	260,772

Table A4: Monthly water demands calculations for Vetch cultivation including effective precipitation and crop evapotranspiration

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days of Month	31	28	31	30	31	30	31	31	30	31	30	31
PE (mm day^{-1})	1.2	1.3	0.7	0.2	0.1	0.0	0.0	0.0	0.0	0.1	0.5	0.9
$\overline{KC}$	1.0	1.0	1.2	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.7
ET_O (mm day^{-1})	1.9	2.3	3.3	4.3	5.1	5.5	5.7	5.4	4.7	3.5	2.3	1.8
ET_C (mm day^{-1})	1.8	2.3	3.8	3.4	0.0	0.0	0.0	0.0	0.0	0.0	1.2	1.3
$ET_{C\text{-net}}$ (mm day^{-1})	0.0	0.0	3.1	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0
Irrigation Efficiency	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
$ET_{C\text{-gross}}$ (mm day^{-1})	0.0	0.0	3.9	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0
$ET_{C\text{-gross}}$ (mm)	0.0	0.0	120.1	120.8	0.0	0.0	0.0	0.0	0.0	0.0	24.9	0.0
Area (ha)	297.6	297.6	297.6	297.6	297.6	297.6	297.6	297.6	297.6	297.6	297.6	297.6
CWR (m^3)	0	0	357,529	359,403	0	0	0	0	0	0	74,134	0
Supply (m^3)	276,768	249,984	276,768	267,840	276,768	267,840	276,768	276,768	267,840	276,768	267,840	276,768
Effluent (m^3)	1,075,178	885,118	961,683	1,094,040	1,134,166	1,075,486	1,119,844	1,123,874	1,088,200	1,090,073	984,269	1,134,133
Surplus/Deficit (m^3)	276,768	249,984	-80,761	-91,564	276,768	267,840	276,768	276,768	267,840	276,768	193,706	276,768

Monthly and annual differences in effective precipitation (Pe), reference evapotranspiration (ETO), and crop water requirements (CWR) among the four crop types (olive, alfalfa, barley, and vetch) were tested using one-way ANOVA at a significance level of $P<0.05$. Where significant effects were observed, Tukey's HSD post-hoc test was employed to identify pairwise differences.

To assess the reliability of model outputs from CROPWAT 8.0, correlation analysis (Pearson's r) was conducted between computed ETO and observed meteorological parameters (temperature and wind velocity). The efficiency of water allocation among crops was further evaluated using descriptive indicators, including Water Use Efficiency (WUE = Yield / CWR) and

Relative Water Supply (RWS = Supply / Demand). Spatial visualization and graphical representation of monthly supply–demand balance were generated using OriginPro 2023 and ArcGIS 10.8, providing heatmaps and temporal trend plots for comparative interpretation.

RESULTS

Climatic Analysis

Rainfall Distribution

Analysis of historical rainfall data from QAIA and Al-Mushaqqar stations (1980-2010) revealed distinct seasonal patterns in precipitation distribution.

The data in Table 3 shows that annual precipitation averaged 157.7mm, with maximum rainfall occurring in January-February (38.6mm and 38.3mm, respectively). The *Pe* was negligible during summer months (June-August), demonstrating the critical need for irrigation during this period.

Table 3: Monthly rainfall and effective precipitation data from QAIA and Al-Mushaqqar stations (1980–2010)

Month	Days of month	Precipitation (mm)	*Pe* (mm)	*Pe* (mm day^{-1})	Dependable precipitation (mm day^{-1})
January	31	38.6	36.2	1.2	0.8
February	28	38.3	36.0	1.3	0.9
March	31	23.3	22.5	0.7	0.5
April	30	5.3	5.3	0.2	0.1
May	31	2.5	2.5	0.1	0.1
June	30	0.1	0.1	0.0	0.0
July	31	0.0	0.0	0.0	0.0
August	31	0.0	0.0	0.0	0.0
September	30	0.1	0.1	0.0	0.0
October	31	4.0	4.0	0.1	0.1
November	30	16.0	15.6	0.5	0.4
December	31	29.4	28.0	0.9	0.6

Reference Evapotranspiration (ET_O)

Reference evapotranspiration *(ET_O)* calculations using the FAO Penman-Monteith equation revealed strong seasonal variations in atmospheric water demand (Fig. 2). The analysis shows that ET_O values peak during the summer months (June–August) at 5.5–5.8mm day^{-1}, while the lowest values were recorded in the winter months (December–February), ranging from 1.82 to 2.33mm day^{-1}.

Crop-Specific Analysis

Land Allocation

Within the 962.5ha of irrigated area around the SAWWTP, four main crops compete for water and space. Vetch occupies 297.6ha (31%), alfalfa 289.0ha (30%), barley 280.4ha (29.1%), and olives 95.5ha (9.9%) (Table 4).

Table 4: Distribution of irrigated areas and water rights requirements by crop type in South Amman

Crop type	Area (ha)	Water rights requirements (m^3)
Olive	95.5 (9.9)	1,045,725 (12.9)
Alfalfa	289.0 (30.0)	3,164,550 (39.1)
Barley	280.4 (29.1)	2,271,240 (28.1)
Vetch	297.6 (30.9)	1,607,040 (19.9)
Total	962.5	8,088,555

Values in parentheses are percentages.

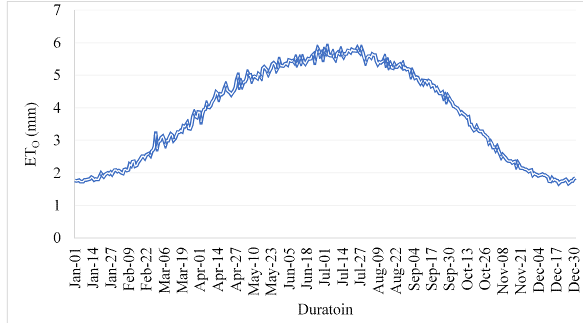

Fig. 2: Monthly patterns of reference evapotranspiration (*ET_O*) (mm) at SAWWTP based on data from QAIA and Al-Mushaqqar stations (estimated by FAO-56 Penman–Monteith for 1980–2010).

Crop Water Requirements (CWR)

The analysis results of the CWR shown in (Fig. 3-5) and Table (A.1 to A.4 in Appendix) reveals the following:

- Olives: Annual demand is 897,529m^3 year^{-1} (12.5% of total), with peak demand in July at 157,702m^3. A water surplus exists from January to April and from October to December. Conversely, a shortage occurs from May to September, with the most severe deficit in July at 30.5% of the gross water requirements. The period from January to February and December shows no water requirement, leading to a complete surplus of the available supply.
- Alfalfa: The highest water consumer at 4,044,134m^3 year^{-1} (56.4% of total demand), with peak monthly demand in July at 699,944m^3. A surplus is recorded from January to March, and again in November and December. However, from April to October, there is a consistent and significant shortage. The most critical shortage is in July, where demand exceeds supply by 61.6%.
- Barley: Annual demand is 1,440,871m^3 year^{-1} (20.1% of total), with peak demand in April at 367,998m^3 and it's clear that there is a water shortage from March to May, with the most severe deficit of 31.4% occurring in April. The crop experiences a surplus in all other months, with a small surplus of 16.3% in June. During the months of January, February, July, August, and December, when there is no water requirement for barley, the full supply is considered a surplus.
- Vetch: The lowest water consumer at 791,067m^3 year^{-1} (11.0% of total), with peak demand in April at 359,403m^3 which resulting in a shortage during March and April. The most significant shortage is in April, with a deficit of 25.48% relative to the water requirement. A surplus exists for the remainder of the year. When the water requirement is zero, such as from May to October, and in January, February, and December, the entire supply represents a surplus.

Water use efficiency varies significantly: olives convert water most economically at about 940,0m^3 ha^{-1} year^{-1}, whereas alfalfa consumes 13,990m^3 ha^{-1} year^{-1}. Barley and vetch follow at 5,130 and 2,660m^3 ha^{-1} year^{-1}, respectively.

Supply-Demand Balance

The SAWWTP produced 12,766,064m^3 of TWW in 2024. Of this total, 7,173,601m^3 (56%) was used for crop

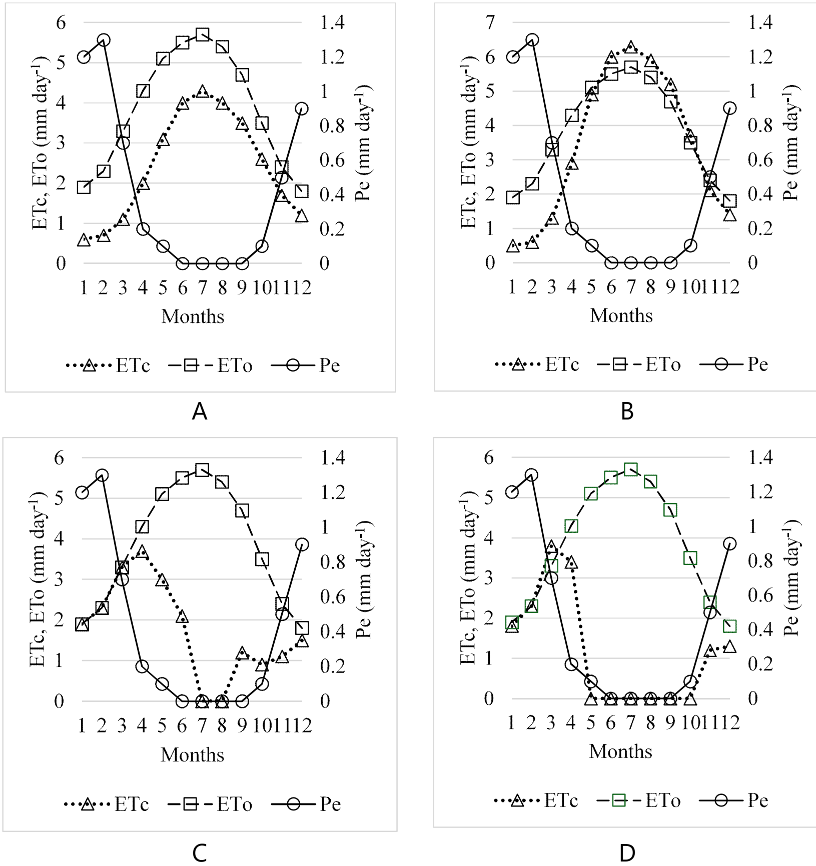

Fig. 3: Monthly time-series of ET_O, Pe, and ET_C for (a) Olive, (b) Alfalfa, (c) Barley, and (d) Vetch.

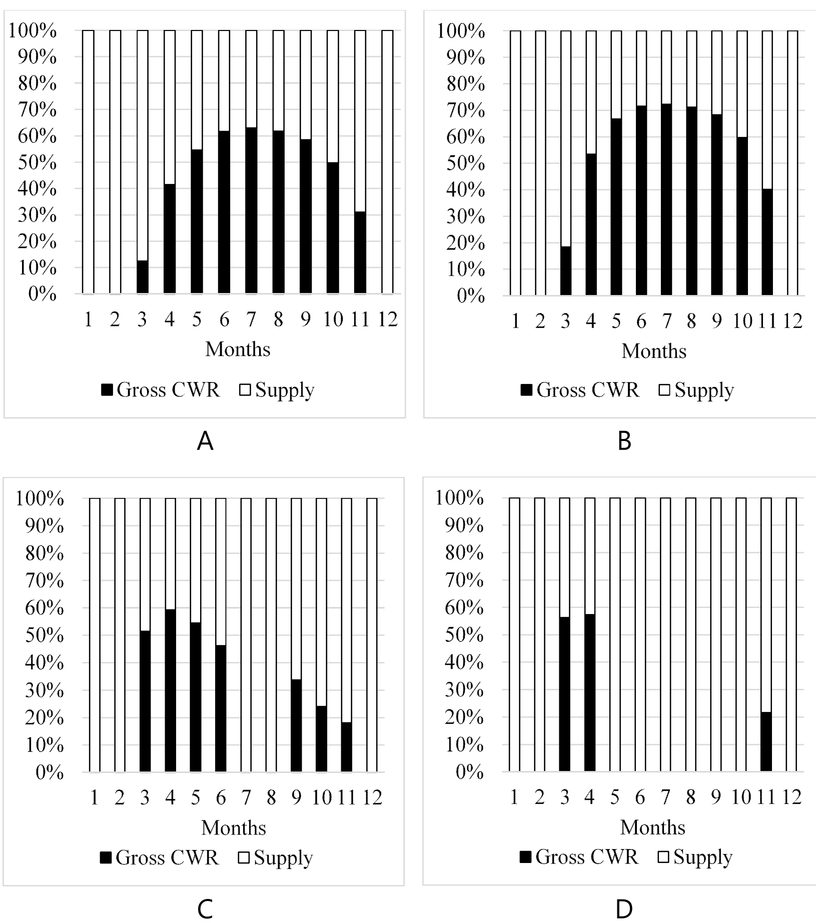

Fig. 4: Stacked monthly gross CWR and supply for (a) Olive, (b) Alfalfa, (c) Barley, and (d) Vetch.

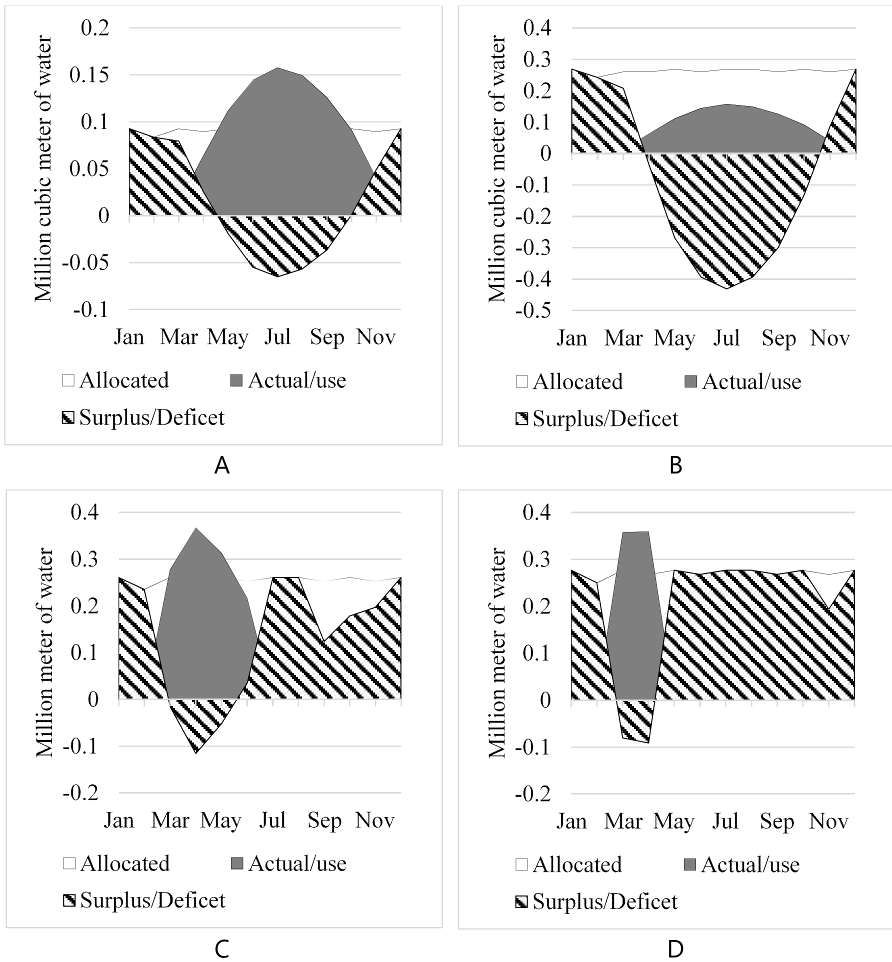

Fig. 5: Allocation, use, and surplus water requirements for (a) Olive, (b) Alfalfa, (c) Barley, and (d) Vetch.

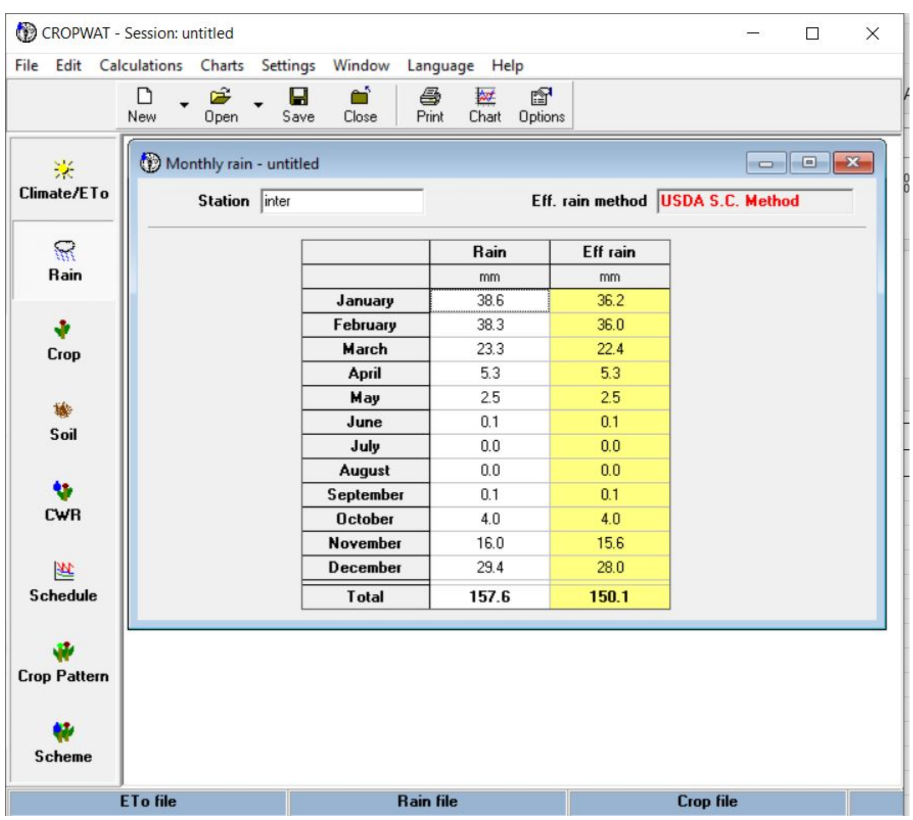

Fig. A1: CROPWAT configuration.

irrigation, leaving a surplus of 5,592,463m³—nearly 44% of the total output. Seasonal alignment is uneven: the period from April to July registers the highest water withdrawal (up to 1,088,670m³ in April), while the winter months (December–February) generate an abundant surplus, supported by natural precipitation (Fig. 6). Table 5 shows the monthly relative percentages of surplus to supply for Olive, Alfalfa, Barley, and Vetch. Table 6 reveals the annual surplus calculated based on two scenarios: water rights allocations and actual requirements, confirming that the surplus is larger when compared to actual needs.

DISCUSSION

The Systemic Inefficiency of Fixed Allocation

This study reveals a fundamental disconnect between the static water allocation system implemented in the South Amman area and the dynamic reality of agriculture. The allocation of a uniform quota of 30 m³ ha⁻¹ day⁻¹ ignores the basic principle that crop water needs are not constant but vary significantly based on crop type, phenological stage, and seasonal climatic conditions. This practice leads to systemic inefficiency, a finding consistent with scientific literature that confirms the failure of rigid volumetric allocation systems to achieve optimal water use, especially in arid regions with limited resources (Wang et al., 2023).

This inefficiency manifests as a dual problem: on one hand, there is an over-allocation of water to crops like barley and vetch, leading to the waste of a total of 1.65 million m³ annually of TWW that was produced at considerable cost. This waste is not only an economic loss but can also lead to environmental problems such as nutrient leaching from the soil and groundwater pollution (Wang et al., 2023). On the other hand, alfalfa, the most water-intensive crop, suffers from an allocation deficit of about 0.88 million m³ annually. This water shortage during peak growth periods can cause water stress to the plant, reducing its productivity and quality, which directly contradicts the goals of enhancing water productivity in agriculture (Mortazavizadeh et al., 2025). The shift towards dynamic allocation systems that respond to actual demand and are guided by real-time evapotranspiration data is no longer a luxury but an imperative for effectively managing scarce water resources (Yao et al., 2025).

Recent experiences from other arid regions demonstrate that dynamic allocation instruments—such as flow metering, ETc-based quotas, and stage-specific irrigation scheduling—can greatly improve equity and efficiency (Fernández García et al., 2020). Integrating digital monitoring of deliveries and linking quotas to crop ETc allow water authorities to adjust distribution in real time, ensuring fairer and more productive use of treated wastewater (Matheri et al., 2022). For Jordan, transitioning toward such adaptive allocation frameworks requires institutional coordination between the Jordan Water Authority and the Ministry of Agriculture in Jordan, along with farmer training on data-driven irrigation management.

Table 1: Surplus to Supply (%) for Olive, Alfalfa, Barley, and Vetch

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Olive	100%	100%	86%	29%	-21%	-61%	-70%	-61%	-41%	1%	55%	100%
Alfalfa	100%	100%	80%	-14%	-100%	-151%	-160%	-147%	-115%	-48%	33%	100%
Barley	100%	100%	-6%	-46%	-20%	14%	100%	100%	49%	68%	78%	100%
Vetch	100%	100%	-29%	-34%	100%	100%	100%	100%	100%	100%	72%	100%

Table 2: Annual water requirements and surplus under water rights requirements versus actual requirements scenarios for 2024

Annual	Effluent (m³)	Water rights requirements (m³)	CWR (m³)
2024	12,766,064	8,088,555	7,173,601
Surplus	-	4,677,509	5,592,463

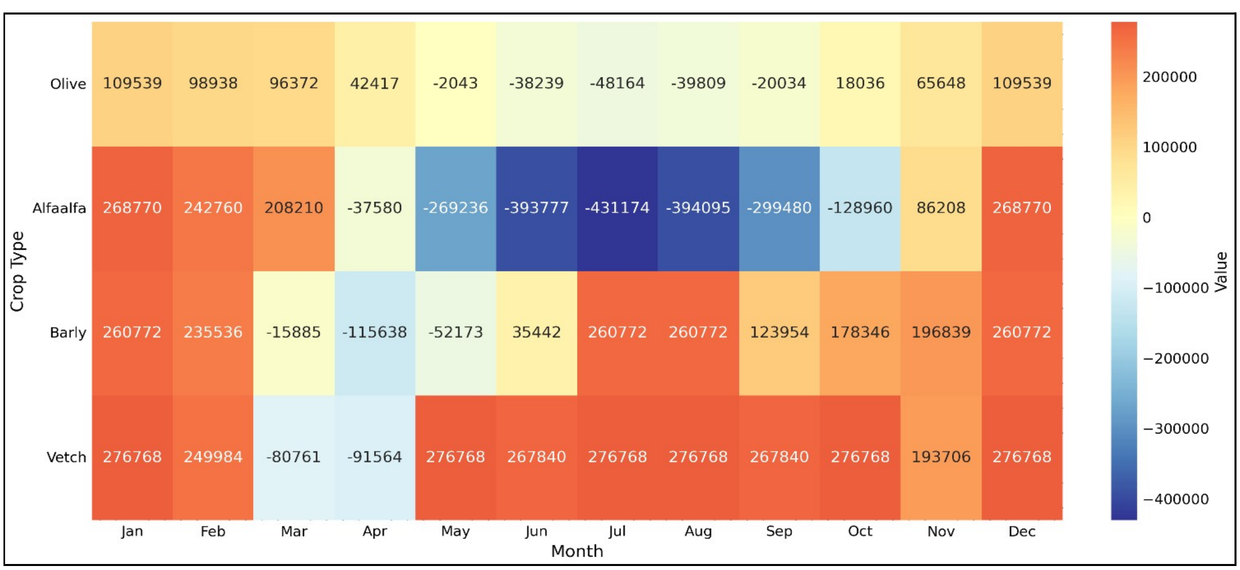

Fig. 6: Heatmap of surplus (crop×month) for (a) Olive, (b) Alfalfa, (c) Barley, and (d) Vetch.

Agricultural and Economic Implications of the Prevailing Crop Portfolio

The analysis of water use efficiency is not limited to how water is allocated but extends to what we grow. The results show a stark contrast in water productivity among different crops. Alfalfa plays the role of the "biggest water consumer," a counting for more than half of the total water demand (56.4%) while occupying less than a third of the area (30%). This high consumption is consistent with what is known about alfalfa as a water-intensive forage crop, especially in arid environments (Ma et al., 2024; Guo et al., 2025; Miao et al., 2025). This reality raises serious questions about the sustainability of its large-scale cultivation in a region suffering from extreme water poverty.

In contrast, olives emerge as a model of efficiency, consuming only 12.5% of the water on 9.9% of the area, achieving the highest water productivity. This finding is supported by recent economic studies in Jordan which have shown that olives not only have high water efficiency but also demonstrate good economic resilience when irrigated with TWW, while maintaining their profitability (Tabieh et al., 2025). While salt-sensitive crops like citrus may be negatively affected, crops such as olives and date palms benefit from the nutrient content in TWW (Yalin et al., 2023).

This contrast leads to a deeper conclusion: the problem is not just in the "mechanism" of allocation, but in the "pattern" of crop selection. The agricultural system in South Amman appears to be locked into cultivating a water-intensive forage crop (alfalfa) that the available TWW supply, even with a significant annual surplus, cannot adequately support under the current allocation system. This represents a structural weakness. Since the National Water Strategy calls for increasing the economic return per cubic meter of water (MWI, 2023), one of the most important avenues for improvement lies not only in reforming the allocation mechanism but also in stimulating a strategic shift in the crop portfolio. Farmers should be encouraged to transition from growing low-value, high-water-consumption fodder to high-value, low-consumption crops that are adaptable to irrigation with TWW, such as olives. This approach reconciles agricultural reality with water scarcity and national economic objectives.

Alfalfa provides high biomass and nutrient uptake under TWW irrigation but entails high consumptive water use compared with barley, vetch, or olives. While alfalfa's market value and contribution to livestock feed justify its cultivation, its low economic return per cubic meter suggests an opportunity for partial substitution by less water-intensive crops (Lauriault et al., 2022). For example, barley and vetch can yield higher water productivity (JD/m^3) under moderate irrigation, while olives, though perennial, offer resilience under deficit conditions. Balancing crop choices based on both agronomic suitability and economic efficiency can enhance overall system sustainability.

Reimagining the Surplus: TWW as an Untapped Strategic Asset

The annual surplus of 5.6 million m^3 of TWW should not be viewed as "wasted water," but as a "strategic asset unexploited due to temporal mismatch." The results clearly show that the TWW supply from the plant is relatively constant throughout the year, whereas agricultural demand is sharply seasonal, peaking in the spring and summer months and declining significantly in winter. This disparity between continuous supply and fluctuating demand is the root cause of a huge surplus in winter (up to 1.1 million m^3 in December alone) and a potential deficit during peak times.

This situation is not unique to Jordan; many arid regions that rely on water reuse face the same challenge. The logical and proven solution is to decouple supply and demand by developing seasonal storage infrastructure (Sträter et al., 2025). Building reservoirs or ponds to collect the winter surplus of TWW would enable its use during peak demand periods in the summer. This action would transform the surplus from a problem into a solution, effectively increasing the "usable supply" of water, providing greater flexibility in irrigation management, enhancing resilience to droughts, and opening the door to the possibility of sustainably expanding irrigated areas (Ward, 2022; Muharomah et al., 2025).

Managing seasonal mismatches between TWW supply and crop demand requires engineered storage and conjunctive-use strategies. Establishing lined lagoons or small reservoirs adjacent to distribution networks can capture winter surpluses for release during summer peaks (Sekar et al., 2024). Integrating storage with gravity-fed or pressurized systems minimizes energy costs, while sediment control and periodic flushing maintain quality (Harne et al., 2024). Coupling such infrastructure with predictive scheduling models would allow Jordan to maximize TWW utilization throughout the year, transforming temporal surplus into a strategic buffer against summer shortages.

Aligning Field Reality with the National Water Strategy

The findings of this study gain particular significance when linked directly to Jordan's high-level water policy objectives. The field-level analysis in South Amman provides not just a local snapshot but serves as a real-world case study for evaluating the implementation effectiveness of the "National Water Strategy (2023–2040)". Table 7 illustrates how the specific findings and recommendations of this study translate directly into actions that support national strategic goals.

The study's findings align directly with the National Water Strategy (2023–2040), which prioritizes maximizing economic return per cubic meter and reducing dependence on freshwater sources. Implementing dynamic allocation and promoting less water-intensive cropping patterns could increase TWW's economic yield while supporting national substitution targets. Moreover, strengthening farmer engagement through incentives, extension services, and cost-sharing programs is essential to enhance adoption. These steps collectively advance the Strategy's objectives for water-use efficiency, climate resilience, and equitable resource management.

Table 3: Alignment of study findings with the objectives of Jordan's National Water Strategy (2023–2040)

Objective in the National Water Strategy (2023–2040)	Relevant Finding
Reform irrigation practices, and replace (freshwater) with non-conventional sources.	**Finding:** The South Amman system relies entirely on TWW, demonstrating policy implementation. However, the *method* of use is inefficient.
Improve on-farm water use efficiency through innovative technologies and improved irrigation water management.	**Finding:** The fixed allocation (30 m^3 ha^{-1} day^{-1}) is inefficient, causing an over-allocation of 1.65 million m^3 for barley/vetch and an under-allocation of 0.88 million m^3 for alfalfa. **Recommendation:** Transition to a dynamic, crop-specific allocation system based on real-time ETc data.
Increase cultivation of lower water requirement and higher value crops.	**Finding:** Olives show the highest water use efficiency (9,400 m^3 ha^{-1} $year^{-1}$), while alfalfa has the highest demand (13,990 m^3 ha^{-1} $year^{-1}$). **Recommendation:** Incentivize a shift in the crop portfolio from water-intensive fodder (alfalfa) to water-efficient, high-value crops (olives).
Increase the economic return for water used in irrigation to at least 1.1 JOD m^{-3}.	**Finding:** The current system wastes a significant portion of TWW resources on less productive applications. **Recommendation:** By reallocating water according to actual needs and promoting efficient crops, the overall economic productivity of the available water can be significantly increased.
Close the gap between water supply and demand... by increasing supplies from non-conventional sources.	**Finding:** There is an annual TWW surplus of 5.6 million m^3 (44% of supply) but it is temporally mismatched. **Recommendation:** Implement seasonal storage infrastructure (e.g., reservoirs) to capture winter surplus for use during peak summer demand, effectively increasing the *usable* supply.

Study Limitations and Future Research Directions

Although this study provides a comprehensive analysis of the agricultural water budget in the South Amman area, it is important to acknowledge certain limitations that open avenues for future research. First, the current analysis focuses on water and agricultural aspects; there is a need for an integrated economic analysis that assesses the cost-benefit of investing in seasonal storage infrastructure and analyzes the financial implications for farmers of shifting their crop portfolios (Tabieh et al., 2025).

Second, the study did not address the long-term environmental impacts of using TWW on soil health. The accumulation of salts (salinity), nutrients, and heavy metals is a major concern in sustainable reuse systems (Sei et al., 2025). Therefore, conducting longitudinal studies to monitor soil chemistry and crop productivity under TWW irrigation systems is crucial for ensuring long-term sustainability.

Third, the study is limited to technical analysis and overlooks important socio-economic factors, such as the acceptance by farmers of transitioning to new allocation systems or changing their traditional crops. Understanding the potential economic and cultural barriers to adopting these recommendations is essential for designing implementable policies (Tarawneh et al., 2024).

Finally, the analysis relies on historical climate data. Given the expected impacts of climate change on rainfall patterns and temperatures in Jordan (Albatayneh et al., 2024), future research should include climate scenario modeling to assess the resilience and sustainability of the proposed water management system under changing future climatic conditions (Mortazavizadeh et al., 2025).

Long-term sustainability of TWW irrigation depends on continuous environmental monitoring to prevent soil degradation and crop contamination (Alnaimy et al., 2021). Regular testing of soil electrical conductivity (EC), sodium adsorption ratio (SAR), nutrient buildup, and trace metal accumulation should form part of an integrated safeguard program (Baghel & Tripathi, 2025). Monitoring should follow FAO and WHO guidelines, with sampling at least once per season and periodic crop tissue analysis (Lusty et al., 2021). Future research should evaluate cumulative effects of TWW irrigation on soil health, salinity trends, and micronutrient dynamics to ensure safe reuse over successive years.

Conclusion

This study aims to analyze the current situation of the use of TWW at the SAWWTP. It shows that there is a high potential for improvement in the use of water and how resources are used in a way that is good for the environment. The results show that the plant's yearly output of TWW, which is 12,766,064m³, is far more than both the quantity set aside by the present water distribution system 8,088,555m³ and the actual water needs of the crops 7,173,601m³. This means that there is an extra 5,592,463m³ per year and at the same time there is a shortage in water in few months for each crop, which is a big chance for improvement. The study also finds clear seasonal trends in supply and demand. For example, there is a lot of water in the winter and not enough in the summer, when crops are at their optimum. Assessments of crops also show that certain crops are routinely over- or under-allocated water under the existing method, which means that the system is not efficient at using water. The study also shows that the present methods of allocating and supplying water have fundamental issues that make them less efficient, even when there is more water available. This research provides a solid base for continuous system development by correctly quantifying how much water crops are used and describing how supply and demand vary over time. It also enables those who must make decisions to do so based on facts. This backs up the idea of using flexible allocation methods and making infrastructure stronger so that water distribution better meets the needs of farmers.

The findings of this study point to several strategic recommendations for improving the efficiency and sustainability of TWW management at the SAWWTP. Infrastructure development is essential, particularly through the construction of seasonal storage reservoirs to capture excess winter flows, the expansion of distribution networks to fully serve the designated irrigated areas, and the modernization of on-farm irrigation systems with technologies such as drip and subsurface irrigation to reduce losses and improve delivery efficiency. On the policy level, transitioning from the current uniform allocation of 30m³ ha⁻¹ day⁻¹ to a more flexible, crop-specific, and demand-responsive system is critical. This should be accompanied by comprehensive volumetric monitoring through the installation of meters and the introduction of adaptive water distribution schedules that account for seasonal variability and crop growth stages. Agronomic improvements are also necessary, including the promotion of drought-tolerant crops such as olives, the reduction of water-intensive crops like alfalfa, and the diversification of cropping patterns to align with water availability. The identified surplus can be strategically used to expand irrigated areas and introduce new, water-efficient species. Future research should focus on conducting detailed cost-benefit analyses of infrastructure investments and crop adjustments, assessing the long-term impacts of TWW irrigation on soil health and crop productivity, and modeling future water availability under varying climate scenarios. Together, these measures offer a practical and scalable framework for sustainable TWW use, enhancing both agricultural productivity and water security in arid and semi-arid regions.

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Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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